Health Concerns Related to Radiation Exposure of the Female Nuclear Medicine Patient

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The female nuclear medicine patient is of special concern in evaluating radiation dose and risk in nuclear medicine. The female's overall body size and organ sizes generally are smaller than those of her male counterpart (thus her radiation doses will be higher, given the same amounts of administered activity and similar biokinetics); female gonads are inside the body instead of outside and are near several organs often important as source organs in internal dosimetry (urinary bladder, liver, kidneys, intestines); risk of breast cancer is significantly higher among females than males; and in the case of pregnancy, exposure to radiation of the embryo/fetus and the nursing infant are of special concern in such an analysis. All these concerns are addressed in this study through a comparative study of radiation doses for males and females over a large number (~60) of nuclear medicine studies and through a study of what is known about radiation dosimetry in pregnancy and breast feeding. It was found that women's critical organ doses and effective doses (as defined by the International Commission on Radiological Protection 60 [ICRP 60]) are about 25% higher than those for men across all these studies. Women's gonad doses, however, may be as much as 10 to 30 times higher than those in men, although 2- to 3-fold differences are common. Many radiopharmaceuticals are administered to women of childbearing age; however, little is known about how much activity crosses the placenta and about the biokinetics in the fetus should it occur. Nonetheless, dose estimates are provided at four stages of pregnancy (early, 3-month, 6-month, and 9-month gestation) for a large number of radiopharmaceuticals, whether or not quantitative estimates of placental crossover can be made. Many radiopharmaceuticals are also excreted in breast milk of nursing mothers. Breast feeding interruption schedules are suggested through analysis of the observed kinetics of these pharmaceuticals and an assumed dose limit of 1 mSv (effective dose equivalent) to the infant. —*Environ Health Perspect* 105(Suppl 6):1403–1409 (1997)

Key words: radiation, radiation dosimetry, internal dosimetry, nuclear medicine, women's health issues

Introduction

The risk–benefit analysis for patients in nuclear medicine necessarily uses calculated estimates of radiation doses (absorbed dose, dose equivalent, effective dose, etc.) for exposed persons. Analysis is different than that used in other situations, as the person receiving the radiation dose usually is also the one who directly benefits from the exposure. However, the female nuclear medicine patient is of special concern to the evaluation of radiation dose and risk in nuclear medicine. The female's overall body size and organ sizes are generally smaller than those of her male counterpart (thus her radiation doses will be higher, given the same amounts of administered activity and similar biokinetics); female gonads are inside the body instead of outside and are near several organs often important as source organs in internal dosimetry (urinary bladder, liver, kidneys, intestines); risk of breast cancer is significantly higher among females than males; and in the case of pregnancy, exposure of the embryo/fetus and the nursing infant is of special concern in such an analysis. This study analyzes the differences in organ doses and effective doses [as defined in International Commission on Radiological Protection 60 (ICRP 60) (*1*)], and gonad doses between male and female nuclear medicine patients. Radiation dose estimates for many nuclear medicine procedures involving a wide variety of radionuclides and pharmaceuticals (even some that are no longer in common use, in order to broaden the spectrum of observed results) were developed for standard adult males (70 kg) and females (57 kg), and differences in organ, gonad, and effective doses were studied. Results from several previous studies on radiation dosimetry in pregnancy and lactation were included to provide a more complete discussion of women's health concerns in nuclear medicine.

This study provides only estimates of radiation dose for the adult female from nuclear medicine procedures. This information may be used to analyze risks that women might incur from these procedures and to determine how these risks may differ from those incurred by men; such an analysis is outside the scope of this work. Additional information needed to complete such an analysis would include the amount of activity administered per study, the number of studies performed per year, and estimates of the risk incurred per unit of dose received. This information changes frequently and should be obtained at the time any risk–benefit analysis is performed; thus, no attempt was made to include such an analysis in this work.

Methods

A wide variety of nuclear medicine studies (~60) were chosen for the comparative study of organ, gonad, and effective doses between men and women. Standard biokinetic models were taken from ICRP Publication 53 (*2*) or, in some cases, from internal files at the Radiation Internal Dose Information Center (RIDIC) in Oak Ridge, Tennessee. (This center maintains up-to-date information on the kinetics and

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Abbreviations used: ED, effective dose; EDE, effective dose equivalent; ICRP, International Commission on Radiological Protection; RIDIC, Radiation Internal Dose Information Center; USNRC, U.S. Nuclear Regulatory Commission.

Table 1. Critical organ, gonad, and effective doses for females and males for the radiopharmaceuticals studied.

Radiopharmaceutical	Critical organ doses, mGy/MBq			Gonad doses, mGy/MBq		Effective doses, mSv/MBq	
	Females	Males	Organ	Females	Males	Females	Males
Au-198 colloid	12.9	10.6	Spleen	0.12	0.042	1.16E+00	9.14E–01
C-11 Tryptophane	0.0267	0.0245	Kidneys	0.004	0.0028	5.03E–03	4.32E–03
C-11 Iomazenil	0.127	0.099	UBC	0.00437	0.0022	1.39E–02	1.06E–02
Co-57 Vitamin B-12, nor/flsh	30	23	Liver	1.1	0.46	2.90E+00	2.25E+00
Co-57 Vitamin B-12, PA/flsh	3.8	3	Liver	0.3	0.068	5.99E–01	4.90E–01
Co-58 Vitamin B-12, nor/flsh	44	35	Liver	2.65	1	5.45E+00	4.35E+00
Co-58 Vitamin B-12, PA/flsh	5.8	4.7	Liver	1.53	0.22	1.59E+00	1.30E+00
Co-60 Vitamin B-12, nor/flsh	680	550	Liver	37	16	8.01E+01	6.39E+01
Co-60 Vitamin B-12, PA/flsh	88	71	Liver	7.44	2.2	1.24E+01	1.00E+01
F-18 FDG	0.26	0.19	UBC	0.019	0.013	3.10E–02	2.41E–02
F-18 NaF	0.35	0.25	UBC	0.014	0.0078	3.10E–02	2.31E–02
Ga-67 Citrate	0.33	0.32	BS	0.1	0.055	1.20E–01	1.00E–01
Hg-197 Chlormerodrin	2.4	2.2	Kidneys	0.0105	0.006	1.13E–01	9.66E–02
I-123 Hippuran	0.44	0.3	UBC	0.013	0.007	2.90E–02	2.01E–02
I-123 IMP	0.082	0.057	UBC	0.017	0.01	2.34E–02	1.82E–02
I-123 mIBG	0.14	0.094	UBC	0.012	0.0069	2.21E–02	1.66E–02
I-123 NaI	4.1	3.4	Thyroid	0.015	0.0051	2.43E–01	2.00E–01
I-125 HSA	1.58	1.22	Heart wall	0.249	0.167	2.91E–01	2.29E–01
I-125 mIBG	0.3	0.22	Liver	0.02	0.013	4.86E–02	3.63E–02
I-125 NaI	250	210	Thyroid	0.0145	0.0065	1.35E+01	1.13E+01
I-131 Hippuran	2.0	1.4	UBC	0.031	0.017	1.17E–01	8.58E–02
I-131 HSA	3.5	3	Heart wall	0.52	0.35	9.35E–01	7.43E–01
I-131 MAA	2.9	2.3	Lungs	0.0565	0.027	6.06E–01	4.72E–01
I-131 mIBG	1	0.78	Liver	0.093	0.058	1.95E–01	1.49E–01
I-131 NaI	420	340	Thyroid	0.06	0.028	2.24E+01	1.84E+01
I-131 Rose bengal	9	8.4	LLI	0.5	0.037	1.33E+00	1.21E+00
In-111 DTPA	0.64	0.43	UBC	0.032	0.019	5.02E–02	3.56E–02
In-111 Platelets	6.2	5.2	Spleen	0.17	0.09	3.95E–01	3.26E–01
In-111 RBCs	0.91	0.76	Spleen	0.23	0.14	2.24E–01	1.85E–01
In-111 WBCs	7.0	5.9	Spleen	0.16	0.03	4.88E–01	4.09E–01
In-111 Pentetreotide	0.73	0.67	Kidneys	0.06	0.026	1.03E–01	8.14E–02
Kr-81m	0.00025	0.0002	Lungs	1.70E–07	1.00E–08	3.39E–05	2.65E–05
N-13 NH_3	0.0091	0.0069	UBC	0.0022	0.0014	2.56E–03	2.01E–03
P-32 Na_2PO_4	10	10	BS	0.98	0.76	2.29E+00	1.80E+00
Tc-99m Albmn mcrsph	0.074	0.058	Lungs	0.003	0.0015	1.77E–02	1.45E–02
Tc-99m DISIDA	0.12	0.11	GB	0.024	0.0017	2.15E–02	1.78E–02
Tc-99m DMSA	0.21	0.19	Kidneys	0.0045	0.0018	1.07E–02	9.12E–03
Tc-99m DTPA - iv	0.11	0.077	UBC	0.0068	0.0038	9.66E–03	7.09E–03
Tc-99m DTPA - aersl	0.046	0.032	UBC	0.0041	0.0017	7.50E–03	5.76E–03
Tc-99m Glucoheptonate	0.11	0.074	UBC	0.0069	0.0037	1.00E–02	7.42E–03
Tc-99m HDP	0.051	0.052	BS	0.0052	0.0023	6.07E–03	4.80E–03
Tc-99m HEDP	0.058	0.041	UBC	0.0047	0.0026	6.55E–03	4.96E–03
Tc-99m HMPAO	0.058	0.051	GB	0.0051	0.0023	1.29E–02	1.09E–02
Tc-99m HSA	0.025	0.021	Heart wall	0.0051	0.0029	7.54E–03	6.21E–03
Tc-99m MAA	0.085	0.067	Lungs	0.0022	0.0011	1.54E–02	1.20E–02
Tc-99m MAG3	0.2	0.14	UBC	0.0085	0.0046	1.40E–02	9.99E–03
Tc-99m MDP	0.035	0.035	BS	0.0041	0.0023	6.19E–03	4.75E–03
Tc-99m MIBI/stress	0.047	0.04	ULI	0.014	0.0031	1.31E–02	1.07E–02
Tc-99m MIBI/rest	0.058	0.05	ULI	0.018	0.0035	1.63E–02	1.33E–02
Tc-99m Pertechnetate	0.034	0.036	UBC	0.01	0.0033	1.40E–02	1.14E–02
Tc-99m PYP	0.039	0.038	BS	0.0047	0.0026	6.31E–03	4.95E–03
Tc-99m RBCs/*in vitro*	0.03	0.021	UBC	0.0057	0.0033	7.83E–03	6.11E–03
Tc-99m RBCs/*in vivo*	0.019	0.016	Heart wall	0.0058	0.0033	7.59E–03	5.99E–03
Tc-99m RBCs/heat	0.78	0.65	Spleen	0.00208	0.00047	2.66E–02	2.24E–02
Tc-99m Slfr cld/nor	0.11	0.086	Liver	0.0022	0.00022	1.03E–02	8.04E–03
Tc-99m Slfr cld/dis	0.26	0.22	Spleen	0.004	0.00083	1.59E–02	0.32E–02
Tc-99m Slfr cld/oral	0.13	0.12	ULI	0.03	0.00125	2.88E–02	2.68E–02
Tc-99m Teboroxime	0.042	0.036	ULI	0.012	0.0019	1.23E–02	1.00E–02
Tc-99m WBCs	0.22	0.18	Spleen	0.0048	0.00084	1.54E–02	1.29E–02
Tl-201 Chloride	0.66	0.62	Thyroid	0.12	0.2	1.65E–01	2.74E–01
Xe-127, 5-min rebreath	0.00063	0.00049	Lungs	0.00026	0.00016	2.92E–04	2.36E–04
Xe-133, 5-min rebreath	0.0014	0.0011	Lungs	0.00025	0.00018	3.86E–04	3.04E–04

Abbreviations: BS, bone surfaces; UBC, urinary bladder contents; ULI, upper large intestine; LLI, lower large intestine; GB, gall bladder; nor, normal subjects; aersl, aerosol; flsh, flushing dose administered; PA, percutaneous anemia subjects; FDG, flurodeoxyglucose; NaF, sodium fluoride; IMP, iodoamphetamine; mIBG, metaiodobenzylguanidine; NaI, sodium iodide; HSA, human serum albumin; MAA, macroaggregated albumin; DTPA, diethylentriaminpentaacetic acid; RBC, red blood cells; WBC, white blood cells; NH_3, ammonia; Na_2PO_4, sodium phosphate; DISIDA, disofenin (iminodiacetic acid derivative); DMSA, dimercaptosuccinic acid; HDP, hydroxymethylene diphosphonate; HEDP, hydroxyethylidene diphosphonate; HMPAO, hexamethylpropyleneamineoxine; MAG3, mercaptoacetylglycylglycylglycine; MDP, methylene diphosphonate; MIBI, methoxyisobutyl isonitrile; PYP, pyrophosphate; slfr cld, sulfur colloid; dis, diseased subjects; rebreath, rebreathing.

dosimetry of radiopharmaceuticals. In addition to keeping abreast of material in the open literature, RIDIC often has access to information on biokinetics or dosimetry of these agents through its support role of the nuclear medicine community.) Estimates of the residence times (*3*) for all significant source organs were established using standard biokinetic models and employing standard adult male (70 kg) and standard adult female (57 kg) phantoms (*5,6*) as employed in and entered into the MIRDOSE 3.1 software (*4*). Radiation doses per unit administered activity to the critical organ (single organ receiving the highest radiation dose), the gonads, and the breast were noted and compared. In these phantoms, the breast tissue represents the female breast tissue; no comparisons were made with the dose to male breast tissue, as the latter is not easily evaluated. Therefore, only the female breast dose was calculated and tabulated simply for information. Effective doses for males and females were also reported and compared.

Results from two recent studies performed by RIDIC were also included in this study—one on radiation dosimetry for the embryo/fetus for the pregnant nuclear medicine patient and one on the dose to the nursing infant for breast-feeding mothers who received radiopharmaceuticals. Extensive detail on the methods used in these two studies are published elsewhere (*7,8*), so only a brief summary is provided here. For the embryo/fetal dose study , an informal survey of a number of nuclear medicine institutions first was performed to determine what radiopharmaceuticals are commonly administered to women of childbearing age as well as what procedures are used to prevent the inadvertent administration of radiopharmaceuticals to pregnant women. The literature was then studied to find as many sources of information as possible about the placental crossover of radiopharmaceuticals. Much of the available information came from animal studies. Where possible, models of the placental crossover of different radiopharmaceuticals as functions of gestation were developed. Next, residence times for activity in the maternal organs (as used in the comparative studies of organ and gonad doses) were combined with estimated residence times for the placenta and fetus and used with the four phantoms (adult female in early pregnancy, and at 3-month, 6-month, and 9-month gestation) in the MIRDOSE 3.1 software, (*4,6*). There are many radiopharmaceuticals that can be administered to women of childbearing age for which no informationabout placental crossover could be found in the literature. In these cases, radiation dose estimates to the fetus were developed using only an estimate of the residence times in the mother's organs. It was not thought prudent to just assume values for placental crossover (e.g., 0.5, 1, 5%) with no literature support. These radiation doses, therefore, may underestimate fetal doses in cases in which significant placental crossover occurs, but at present they represent the best estimates available. The dose to the embryo/fetus is thus reported for many radiopharmaceuticals at these four assumed stages of pregnancy. In the study on breast feeding, values reported in the literature for the excretion of many radiopharmaceuticals in the breast milk of nursing mothers participating in nuclear medicine studies were used in a standard model for nursing that assumed the infant consumed 1000 ml/day of milk, feeding at 3-hr intervals, starting either immediately (3 hr) after the administration of the pharmaceutical or at fixed interruption times (6-hr, 12-hr, 24-hr, etc.). From this analysis, an estimate was obtained of the activity ingested by the infant; the activity ingested was assumed to be quickly and instantaneously absorbed into the bloodstream and thereafter to have biokinetics in the infant similar to that in the adult. Organ residence times were thus assigned, and organ doses and effective dose equivalents [as defined in ICRP Publication 30 (*9*)] were calculated. Effective dose equivalent (*9*) instead of the effective dose (*1*) was used because the study was commissioned by the U.S. Nuclear Regulatory Commission (USNRC), which still uses the effective dose equivalent as its regulatory basis. [The numerical difference between effective dose equivalent and effective dose in nuclear medicine doses is usually very small (*10*).] The USNRC assigned an acceptable dose level of 1 mSv effective dose equivalent to the infant. If the worst-case dose to the infant did not exceed this amount, no interruption of breast feeding was indicated; otherwise the time interval was calculated for which breast feeding had to be stopped to ensure a dose below this level.

Results

Table 1 shows the actual critical organ doses, gonad doses, and effective doses for

Table 2. Ratios of critical organ, gonad, and effective doses for females/males for the radiopharmaceuticals studied.

	Ratios				Ratios		
Radiopharmaceutical	Critical organ	Gonad	ED	Radiopharmaceutical	Critical organ	Gonad	ED
Au-198 Colloid	1.22	2.86	1.27	Kr-81m	1.25	17.00	1.28
C-11 Tryptophane	1.09	1.43	1.16	N-13 NH_3	1.32	1.57	1.27
C-11 Iomazenil	1.28	1.99	1.31	P-32 Na_2PO_4	1.00	1.29	1.27
Co-57 B-12, nor/flsh	1.30	2.39	1.29	Tc-99m Albmn mcrsph	1.28	2.00	1.22
Co-57 B-12, PA/flsh	1.27	4.41	1.22	Tc-99m DISIDA	1.09	14.12	1.21
Co-58 B-12, nor/flsh	1.26	2.65	1.25	Tc-99m DMSA	1.11	2.50	1.17
Co-58 B-12, PA/flsh	1.23	6.95	1.22	Tc-99m DTPA-iv	1.43	1.79	1.36
Co-60 B-12, nor/flsh	1.24	2.31	1.25	Tc-99m DTPA-aersl	1.44	2.41	1.30
Co-60 B-12, PA/flsh	1.24	3.38	1.24	Tc-99m Glucoheptonate	1.49	1.86	1.35
F-18 FDG	1.37	1.46	1.29	Tc-99m HDP	0.98	2.26	1.26
F-18 NaF	1.40	1.79	1.34	Tc-99m HEDP	1.41	1.81	1.32
Ga-67 Citrate	1.03	1.82	1.20	Tc-99m HMPAO	1.14	2.22	1.18
Hg-197 Chlormerodrin	1.09	1.75	1.17	Tc-99m HSA	1.19	1.76	1.21
I-123 Hippuran	1.47	1.86	1.44	Tc-99m MAA	1.27	2.00	1.28
I-123 IMP	1.44	1.70	1.29	Tc-99m MAG3	1.43	1.85	1.40
I-123 mIBG	1.49	1.74	1.33	Tc-99m MDP	1.00	1.78	1.30
I-123 NaI	1.21	2.94	1.22	Tc-99m MIBI-stress	1.18	4.52	1.22
I-125 HSA	1.30	1.49	1.27	Tc-99m MIBI-rest	1.16	5.14	1.23
I-125 mIBG	1.36	1.54	1.34	Tc-99m Pertechnetate	0.94	3.03	1.23
I-125 NaI	1.19	2.23	1.19	Tc-99m PYP	1.03	1.81	1.27
I-131 Hippuran	1.43	1.82	1.36	Tc-99m RBCs/*in vitro*	1.43	1.73	1.28
I-131 HSA	1.17	1.49	1.26	Tc-99m RBCs/*in vivo*	1.19	1.76	1.27
I-131 MAA	1.26	2.09	1.28	Tc-99m RBCs/heat	1.20	4.43	1.19
I-131 mIBG	1.28	1.60	1.31	Tc-99m Slfr cld/nor	1.28	10.00	1.28
I-131 NaI	1.24	2.14	1.22	Tc-99m Slfr cld/dis	1.18	4.82	1.20
I-131 Rose bengal	1.07	13.51	1.10	Tc-99m Slfr cld/oral	1.08	24.00	1.07
In-111 DTPA	1.49	1.68	1.41	Tc-99m Teboroxime	1.17	6.32	1.23
In-111 Platelets	1.19	1.89	1.21	Tc-99m WBCs	1.22	5.71	1.19
In-111 RBCs	1.20	1.64	1.21	Tl-201 Chloride	1.06	0.60	0.60
In-111 WBCs	1.19	5.33	1.19	Xe-127, 5-min rebreath	1.29	1.63	1.24
In-111 Pentetreotide	1.09	2.31	1.27	Xe-133, 5-min rebreath	1.27	1.39	1.27
				Means	1.23	3.54	1.25
				Standard deviations	0.14	4.09	0.11

ED, effective dose.

Table 3. Breast doses estimated for the radiopharmaceuticals studied.

Radiopharmaceutical	Breast dose, mGy/MBq	Radiopharmaceutical	Breast dose, mGy/MBq
Au-198 colloid	0.124	Kr-81m	4.60e-06
Co-57 B-12, Nor/flsh	0.986	N-13 NH_3	0.00163
Co-57 B-12, PA/flsh	0.126	P-32 Na_2PO_4	0.98
Co-58 B-12, Nor/flsh	2.47	Tc-99m Albmn Mcrsph	0.00516
Co-58 B-12, PA/flsh	0.327	Tc-99m DMSA	0.00173
Co-60 B-12, Nor/flsh	39.7	Tc-99m DTPA-iv	0.00137
Co-60 B-12, PA/flsh	5.08	Tc-99m DTPA-aersl	0.00162
F-18 FDG	0.0117	Tc-99m Glucoheptonate	0.00141
F-18 NaF	0.00337	Tc-99m HDP	0.00163
Ga-67 Citrate	0.0592	Tc-99m HEDP	0.00133
Hg-197 Chlormerodrin	0.00501	Tc-99m HMPAO	0.0023
I-123 Hippuran	0.000236	Tc-99m HSA	0.00457
I-123 IMP	0.011	Tc-99m MAA	0.00551
I-123 mIBG	0.00515	Tc-99m MAG3	0.000142
I-123 NaI	0.0039	Tc-99m MDP	0.00121
I-125 HSA	0.207	Tc-99m MIBI/stress	0.00212
I-125 mIBG	0.0156	Tc-99m Pertechnetate	0.00207
I-125 NaI	0.00889	Tc-99m PYP	0.00192
I-131 Hippuran	0.000935	Tc-99m RBCs/*in vitro*	0.00382
I-131 HSA	0.509	Tc-99m RBCs/*in vivo*	0.00414
I-131 MAA	0.0988	Tc-99m RBCs/heat	0.00185
I-131 mIBG	0.0665	Tc-99m Slfr cld/nrml	0.00268
I-131 NaI	0.0556	Tc-99m Slfr cld/dis	0.00236
I-131 Rose bengal	0.00694	Tc-99m Slfr cld/oral	0.000491
In-111 DTPA	0.00447	Tc-99m Teboroxime	0.0026
In-111 Platelets	0.113	Tc-99m WBCs	0.00224
In-111 RBCs	0.137	Tl-201 Chloride	0.0407
In-111 WBCs	0.0802	Xe-127, 5-min rebreath	0.000182
In-111 Pentetreotide	0.0155	Xe-133, 5-min rebreath	0.00023

the radiopharmaceuticals studied in this report. Table 2 shows the ratios of these quantities for the reference adult female/reference adult male. Table 3 shows the breast doses estimated for the adult female for the radiopharmaceuticals studied in this report. Figures 1 to 3 show plots of these results, in histogram format. Figure 4 shows a plot of the breast doses, also in histogram format. The x axes in Figures 1 and 3 are linear and in Figures 2 and 4 logarithmic.

Table 4 is a summary of absorbed doses to the fetus from administration of radiopharmaceuticals to pregnant women (*7*). These doses are expressed as absorbed dose to the embryo/fetus per unit activity administered to the mother. Shaded rows in the table indicate that some information was available on placental crossover and was used in the estimates. Table 5 is a summary of the recommendations for possible interruption of breast feeding in the nursing mother given a radiopharmaceutical, given the 1-mSv infant dose criterion. Further details on the dosimetry are given in the USNRC (*8*).

Discussion

As seen in Table 2 and in Figures 1 and 3, the ratio of the standard female's critical organ doses and effective doses over a wide

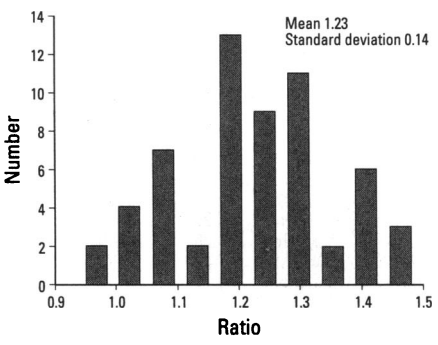

Figure 1. Frequency plot of the ratios (female/male) of critical organ doses calculated in this study.

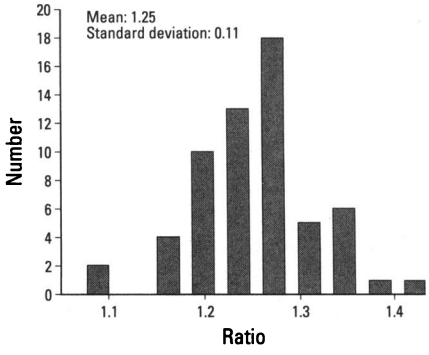

Figure 3. Frequency plot of the ratios (female/male) of effective doses calculated in this study.

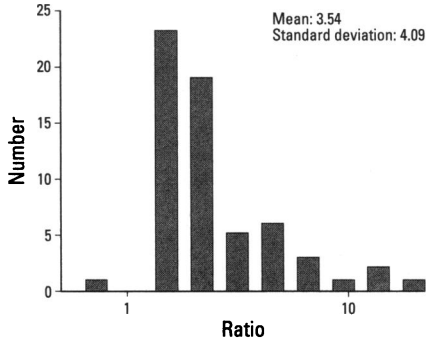

Figure 2. Frequency plot of the ratios (female/male) of gonad doses calculated in this study.

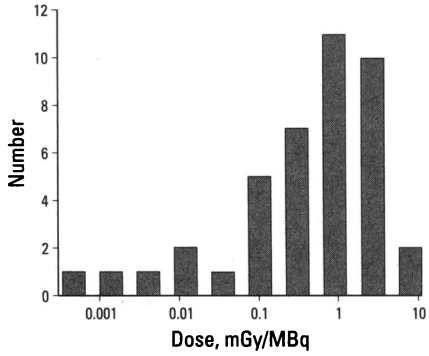

Figure 4. Frequency plot of the female breast doses calculated in this study.

Table 4. Absorbed dose estimates to the embryo/fetus per unit activity of radiopharmaceutical administered to the mother (shading indicates maternal and fetal self-dose contributions) [a]

Radiopharmaceutical	Type of pregnancy			
	Early, mGy/MBq	3-Month, mGy/MBq	6-Month, mGy/MBq	9-Month,mGy/MBq
Co-57 Vitamin B-1, nor/flsh	1.0E+00	6.8E-01	8.4E-01	8.8E-01
Co-57 Vitamin B-12, nor - no flsh	1.5E+00	1.0E+00	1.2E+00	1.3E+00
Co-57 Vitamin B-12, PA - flsh	2.1E-01	1.7E-01	1.7E-01	1.5E-01
Co-57 Vitamin B-12, PA - no flsh	2.8E-01	2.1E-01	2.2E-01	2.0E-01
Co-58 Vitamin B-12, nor - flsh	2.5E+00	1.9E+00	2.1E+00	2.1E+00
Co-58 Vitamin B-12, nor - no flsh	3.7E+00	2.8E+00	3.1E+00	3.1E+00
Co-58 Vitamin B-12, PA - flsh	8.3E-01	7.4E-01	6.4E-01	4.8E-01
Co-58 Vitamin B-12, PA - no flsh	9.8E-01	8.5E-01	7.6E-01	6.0E-01
Co-60 Vitamin B-12, nor - flsh	3.7E+01	2.8E+01	3.1E+01	3.2E+01
Co-60 Vitamin B-12, nor - no flsh	5.5E+01	4.2E+01	4.7E+01	4.7E+01
Co-60 Vitamin B-12, PA - flsh	5.9E+00	4.7E+00	4.8E+00	4.5E+00
Co-60 Vitamin B-12, PA - no flsh	8.3E+00	6.5E+00	6.8E+00	6.5E+00
F-18 FDG	2.7E-02	1.7E-02	9.4E-03	8.1E-03
F-18 Sodium fluoride	2.2E-02	1.7E-02	7.5E-03	6.8E-03
Ga-67 Citrate	9.3E-02	2.0E-01	1.8E-01	1.3E-01
I-123 Hippuran	3.1E-02	2.4E-02	8.4E-03	7.9E-03
I-123 IMP	1.9E-02	1.1E-02	7.1E-03	5.9E-03
I-123 MIBG	1.8E-02	1.2E-02	6.8E-03	6.2E-03
I-123 Sodium iodide	2.0E-02	1.4E-02	1.1E-02	9.8E-03
I-124 Sodium iodide	1.4E-01	1.0E-01	5.9E-02	4.6E-02
I-125 HSA	2.5E-01	7.8E-02	3.8E-02	2.6E-02
I-125 IMP	3.2E-02	1.3E-02	4.8E-03	3.6E-03
I-125 MIBG	2.6E-02	1.1E-02	4.1E-03	3.4E-03
I-125 Sodium iodide	1.8E-02	9.5E-03	3.5E-03	2.3E-03
I-126 Sodium iodide	7.8E-02	5.1E-02	3.2E-02	2.6E-02
I-130 Sodium iodide	1.8E-01	1.3E-01	7.6E-02	5.7E-02
I-131 Hippuran	6.4E-02	5.0E-02	1.9E-02	1.8E-02
I-131 HSA	5.2E-01	1.8E-01	1.6E-01	1.3E-01
I-131 MAA	6.7E-02	4.2E-02	4.0E-02	4.2E-02
I-131 MIBG	1.1E-01	5.4E-02	3.8E-02	3.5E-02
I-131 Sodium iodide	7.2E-02	6.8E-02	2.3E-01	2.7E-01
I-131 Rose bengal	2.2E-01	2.2E-01	1.6E-01	9.0E-02
In-111 DTPA	6.5E-02	4.8E-02	2.0E-02	1.8E-02
In-111 Pentetreotide	8.2E-02	6.0E-02	3.5E-02	3.1E-02
In-111 Platelets	1.7E-01	1.1E-01	9.9E-02	8.9E-02
In-111 RBCs	2.2E-01	1.3E-01	1.1E-01	8.6E-02
In-111 WBCs	1.3E-01	9.6E-02	9.6E-02	9.4E-02
Tc-99m Albm mcrsph	4.1E-03	3.0E-03	2.5E-03	2.1E-03
Tc-99m Disofenin	1.7E-02	1.5E-02	1.2E-02	6.7E-03
Tc-99m DMSA	5.1E-03	4.7E-03	4.0E-03	3.4E-03
Tc-99m DTPA	1.2E-02	8.7E-03	4.1E-03	4.7E-03
Tc-99m DTPA aerosol	5.8E-03	4.3E-03	2.3E-03	3.0E-03
Tc-99m Glucoheptonate	1.2E-02	1.1E-02	5.3E-03	4.6E-03
Tc-99m HDP	5.2E-03	5.4E-03	3.0E-03	2.5E-03
Tc-99m HEDP	7.2E-03	5.2E-03	2.7E-03	2.4E-03
Tc-99m HMPAO	8.7E-03	6.7E-03	4.8E-03	3.6E-03
Tc-99m Human serum albumin	5.1E-03	3.0E-03	2.6E-03	2.2E-03
Tc-99m MAA	2.8E-03	4.0E-03	5.0E-03	4.0E-03
Tc-99m MAG3	1.8E-02	1.4E-02	5.5E-03	5.2E-03
Tc-99m MDP	6.1E-03	5.4E-03	2.7E-03	2.4E-03
Tc-99m MIBI, rest	1.5E-02	1.2E-02	8.4E-03	5.4E-03
Tc-99m MIBI, stress	1.2E-02	9.5E-03	6.9E-03	4.4E-03
Tc-99m Pertechnetate	1.1E-02	2.2E-02	1.4E-02	9.3E-03
Tc-99m PYP	6.0E-03	6.6E-03	3.6E-03	2.9E-03
Tc-99m RBC, heat treated	1.7E-03	1.6E-03	2.1E-03	2.2E-03
Tc-99m RBC, *in vitro*	6.8E-03	4.7E-03	3.4E-03	2.8E-03
Tc-99m RBC, *in vivo*	6.4E-03	4.3E-03	3.3E-03	2.7E-03
Tc-99m Sulfur colloid, normal	1.8E-03	2.1E-03	3.2E-03	3.7E-03
Tc-99m Sulfur colloid, liver disease	3.2E-03	2.5E-03	2.8E-03	2.8E-03
Tc-99m Teboroxime	8.9E-03	7.1E-03	5.8E-03	3.7E-03
Tc-99m WBCs	3.8E-03	2.8E-03	2.9E-03	2.8E-03
Tl-201 Chloride	9.7E-02	5.8E-02	4.7E-02	2.7E-02
Xe-127, 5-min rebreath, 5-liter spirometer vol	4.3E-04	2.4E-04	1.9E-04	1.5E-04

(*Continued on next page*)

Table 4. (*Continued*)

Radiopharmaceutical	Type of pregnancy			
	Early, mGy/MBq	3-Month, mGy/MBq	6-Month, mGy/MBq	9-Month, mGy/MBq
Xe-127, 5-min rebreath, 7.5-liter spirometer volume	2.3E-04	1.3E-04	1.0E-04	8.4E-05
Xe-127, 5-min rebreath, 10 liter spirometer volume	2.3E-04	1.4E-04	1.1E-04	9.2E-05
Xe-133, 5-min rebreath, 5-liter spirometer volume	4.1E-04	4.8E-05	3.5E-05	2.6E-05
Xe-133, 5-min rebreath, 7.5 liter spirometer volume	2.2E-04	2.6E-05	1.9E-05	1.5E-05
Xe-133,-5 min rebreath, 10-liter spirometer volume	2.5E-04	2.9E-05	2.1E-05	1.6E-05
Xe-133, injection	4.9E-06	1.0E-06	1.4E-06	1.6E-06

[a]Data from Russell et al. (*7*).

Table 5. Summary of recommendations for radiopharmaceuticals excreted in the breast milk.

Radiopharmaceutical	Administered activity, MBq (mCi)	Counseling needed?	Advisory	Comments
Ga-67 Citrate	185 (5.0)	Yes	Cessation	
Tc-99m DTPA	740 (20)	No		
Tc-99m MAA	148 (4)	Yes	12 hr	
Tc-99m Pertechnetate	1110 (30)	Yes	24 hr	
I-131 NaI	5550 (150)	Yes	Cessation	
Cr-51 EDTA	1.85 (0.05)	No		
Tc-99m DISIDA	300 (8)	No		
Tc-99m Glucoheptonate	740 (20)	No		
Tc-99m HAM	300 (8)	No		
Tc-99m MIBI	1110 (30)	No		
Tc-99m MDP	740 (20)	No		
Tc-99m PYP	740 (20)	No		
Tc-99m RBCs/*in vivo*	740 (20)	Yes	12 hr	
Tc-99m RBCs/*in vitro*	740 (20)	No		
Tc-99m sulfur colloid	444 (12)	Yes	12 hr	
In-111 WBCs	18.5 (0.5)	Yes	12 hr	
I-123 NaI	14.8 (0.4)	No		
I-123 OIH	74 (2)	No		No consideration of free iodide
I-123 mIBG	370 (10)	Yes	24 hr	No consideration of free iodide
I-125 OIH	0.37 (0.01)	No		No consideration of free iodide
I-131 OIH	11.1 (0.3)	No		No consideration of free iodide
Tl-201	111 (3)	Yes	168 hr	
Tc-99m DTPA aerosol	37 (1)	No		Fraction of administered activity (0.41) treated as iv DTPA
Tc-99m WBCs	185 (5)	Yes	24 hr	Treated as Tc-99m pertechnetate
Tc-99m MAG3	370 (10)	No		Treated as Tc-99m DTPA
Xe-133 gas		No		

[a]Data from the USNRC (*8*).

range of studies is about 1.25, with a relatively small standard deviation (less than 10%). This is reasonable based on the ratio of body weights (57 kg vs 70 kg), which represents about a 20% difference. Individual organ differences vary, but these differences basically represent the effect of the smaller mass. The gonad doses, however, have a mean ratio of about 3.5, with a very wide standard deviation. If a few of the highest gonad dose ratios are omitted (four entries with ratios > 10), the mean and standard deviations are 2.6 and 1.67, respectively. Thus, it appears that the gonad dose ratio is typically a factor of 2 to 3, but that it can vary widely. Therefore, a woman carries a somewhat higher radiation burden than her male counterpart, given the same amount of activity administered per study. If the activity given were scaled based on individual body mass, however, at least the critical organ and effective dose differences would be eliminated. This is not routine in nuclear medicine practice. The amount of activity administered is often scaled by body mass in pediatric studies, but in adults, generally the same amount of activity is given, based on a number of criteria, so the differences reported here are generally realized in practice. Breast doses (Table 3, Figure 4) vary widely between procedures, from a few Gy per MBq, to a few tens of mGy per MBq.

Fetal doses for most radiopharmaceuticals, when expressed on the basis of dose to the fetus per unit activity administered to the mother, for most radiopharmaceuticals tend to decrease throughout gestation. As the baby grows, the absorbed fractions for the fetus absorbing radiation from maternal organs will increase, but the baby's increase in mass generally offsets this increase (recall that absorbed dose is energy absorbed per unit mass). Exceptions to this occur in cases in which there is a considerable increase in the placental crossover of the radiopharmaceutical as pregnancy progresses, which increases fetal self-dose. Some exceptions also occur for certain organs in the mother's body for which the specific absorbed fraction increases throughout gestation, notably the liver, lungs, and spleen (*6*). The doses shown in this report give only the average absorbed dose to the whole fetus; current models do not permit adequate modeling of the dose to individual organs within the fetus, although this may be quite important in many circumstances. Some authors (*11,12*) have attempted on an individual basis to make such individual organ dose estimates. The most notable of these inquiries is that of Watson (*11*), who demonstrated clearly the importance of the dose to the fetal thyroid for iodine (especially I-131) administration to women after week 10 of gestation.

The dose estimate analysis for the nursing infant reveals that for many radiopharmaceuticals no interruption of breast feeding is indicated, even given the relatively low effective dose equivalent criterion of 1 mSv EDE and a use of the worst case values of breast milk concentration and elimination half-time. Many radiopharmaceuticals have short physical half-lives and

decay quickly after administration. Also, because of their short half-lives and their radiation spectrum, most of these nuclides give a fairly low dose per unit intake. A few of the Tc-99m compounds and one I -123 compound required short interruption periods so as not to exceed the 1-mSv effective dose equivalent value. A difference was seen between *in vivo*- and *in vitro*-labeled Tc-99m red blood cells, as the former have a higher assumed fraction of free pertechnetate in the injectate—Tc-99m pertechnetate required a 24-hr interruption to satisfy the dose criterion. The most important compounds in the analysis were I-131 NaI, Ga-67 citrate, and Tl-201 chloride. Because of either their long physical or biological half-times or their high radiation dose per unit intake values, or both, these compounds have the potential for relatively high infant doses, and if these studies are used, cessation of breast feeding is probably indicated.

In summary, it is clear that there are special concerns with regard to the female nuclear medicine patient in the risk/benefit analyses. The most important concerns arise when a woman is either pregnant or breast feeding, but the slightly higher organ and gonad radiation burdens a woman carries compared to her male counterpart are also of interest. A logical extension of this work would be to apply the amount of activity administered per study and the number of nuclear medicine studies performed on men and women for each type of study and to examine the population doses identified in routine nuclear medicine practice. Such information was not available at the time of this writing, but this study provides information that could be used for this analysis should it be undertaken.

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